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Poster paper

Thermo-mechanical analyses of mirror for NSLS-II beamline

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Finite-element analysis (FEA) is utilized to model the temperature distribution and heat-induced deformation of the first mirror of the coherent soft X-ray beamline at NSLS-II. The FEA results of the cooling design show a thermal bump on the area illuminated by the beam plus an overall mirror bending. The resulting slope errors are almost linear over the area where the power is absorbed and have a complex dependence on the mirror thickness. The linear change of the slope error means a constant convex radius of curvature whose defocusing effect can be corrected with a bendable mirror positioned downstream in the beamline. In this paper we discuss the design optimization of the mirror thickness using FEA as a tool.

1. Introduction

The design of NSLS-II, a new state-of-the-art medium-energy third-generation storage ring, is intended to provide ultra-high-brightness X-ray sources. The high brightness of the new third-generation machines is quickly reduced by the quality of the optics, filters, crystals and the heat-induced deformation on the optics. Frequent use of finite-element analysis (FEA) is made for evaluating the thermal response and for optimizing the design and the cooling of the optical elements. The coherent soft X-ray beamline at NSLS-II (Reininger *et al.* 2008) will utilize an internally water-cooled mirror (M1) for absorbing power from unwanted high undulator harmonics. M1 deflects the beam by 2.5° in the non-dispersive direction, thereby significantly reducing the heat load on the optics deflecting in the dispersion plane and determining the monochromator resolution. The source chosen for this beamline is actually two 2 m long 49 mm period elliptically polarized undulators capable of delivering up to 9.0 kW of radiation power with an on-axis power density of 32 kW mrad^{-2}. In the following section we discuss the FEA conducted on this mirror to ensure that the effects of the heat load resulting from high-power photon beams delivered by the insertion device do not affect the desired performance.

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2. Heat load analyses – FEA analysis of the M1 mirror

The mirror (500 mm length × 100 mm width) is located at a distance of 27 m from the source. When the undulators are tuned to emit horizontally polarized radiation at 180 eV, this Au-coated mirror absorbs ~1.6 kW with a maximum power density of 0.85 $\mathrm{W\,mm^{-2}}$. The tabular power density used for defining the heat load on the FEA model was computed using the SRCalc code (Reininger 2011). The mirror is water cooled via 11 channels (5 mm height, 1 mm width, 1 mm from the beam incident surface and 1.5 mm gap between the channels) that run along the length of the mirror. A bulk water temperature of 20°C and a film coefficient of 0.01 W $\mathrm{mm^{-2}\,K^{-1}}$, for the convection boundary condition in the channels were assumed in the calculations. For a hydraulic diameter (=4 × area/perimeter) of 1.67 mm, the above-mentioned convection coefficient can be easily obtained with a flow rate of less than 0.1 gpm (Sieder Tate correlation). The low water flow rate will ensure laminar flow and hence minimize flow vibrations.

The following material properties for silicon were used in the analyses: thermal conductivity: 0.2 W $\mathrm{mm^{-1}\,K^{-1}}$, Young's modulus: 1.31×10^{5} MPa, Possion's ratio: 0.28 and a coefficient of thermal expansion: 2.24 $\mathrm{\mu m\,m^{-1}\,K^{-1}}$. The analyses were conducted using ANSYS Workbench software. A fine mesh density was used within the beam foot print (7.8 mm × 350 mm).

As shown in figure 1, analysis results showed that increasing the number of channels from 11 to 21 did not have a big advantage in terms of reducing the bulk temperature (38.17°C with 11 channels and 38.0°C with 21 channels).

The effect of the mirror thickness on the induced thermal deformation was evaluated by conducting analyses for mirror thicknesses varying from 20 to 100 mm. The resulting meridional slope errors along the length at half the mirror width are summarized in figure 2(*a*). As seen in the figure, the slope error decreases with increasing the mirror thickness. Furthermore, for all thicknesses, the slope changes linearly over ±100 mm, indicating a constant radius of curvature for a given thickness. Since the illumination by the central cone of the first harmonic is narrower than 200 mm, the constant radius of curvature can be compensated by a bendable mirror downstream M1 as discussed by Reininger *et al.* (2008)

The peak-to-peak change in slope (s) over ±100 mm obtained from figure 2(*a*) is plotted in figure 2(*b*) as a function of the mirror thickness (t). The solid line is a fit to the data assuming $s = a{\cdot}t^{-1} + b{\cdot}t^{-3}$. As seen in the figure, the agreement is

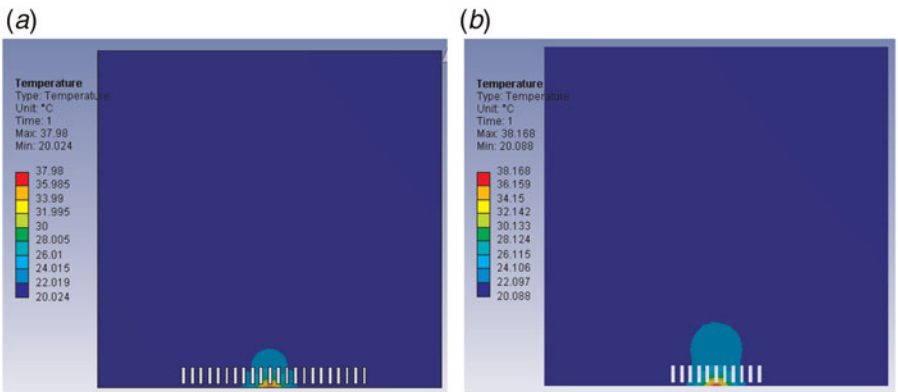

FIGURE 1. Temperature contour plot: (*a*) 21 fins, (*b*) 11 fins.

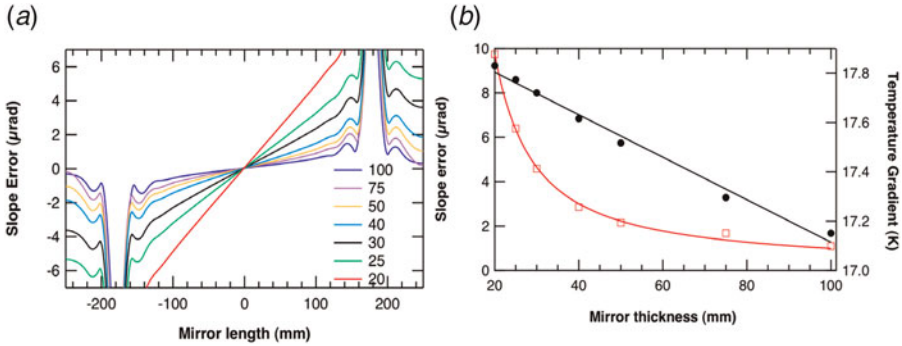

FIGURE 2. (*a*) Meridional slope error for varying mirror thicknesses, (*b*) slope error (open squares) and temperature gradient (full circles) vs. mirror thickness.

very good, indicating that the slope is a superposition of a term due to beam bending (t^{-3}) and a term inversely proportional to the mirror thickness due to thermal 'bump'.

At a mirror thickness of 50 mm, the convex radius of curvature is slightly less than 100 km. This curvature will generate a virtual source located at 27.7 m upstream of the mirror instead of the nominal 27 m. This variation in the horizontal source position can be easily corrected by using an aperture downstream M1 that transmits only the reflected beam from the region where the slope is linear, followed by a bendable mirror as described by Reininger *et al.* (2008). For completeness, we also plot in figure 2(*b*) the temperature gradient (temperature difference between the maximum and the bulk mirror temperature) as a function of the mirror thickness. The variation over the thicknesses investigated is linear with a total change of less than a degree.

3. Conclusions

The thickness of the first optical element of the coherent soft X-ray beamline at NSLS-II was optimized to minimize the heat-induced deformations. We have found that the slope error can be greatly reduced by increasing the mirror thickness. In the case studied here, which is typical for soft X-ray beamlines, already a thickness of 50 mm is sufficient to significantly reduce the meridional slope error.

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